

Ultra-high-energy-cosmic-ray hotspots from tidal disruption events

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ABSTRACT

We consider the possibility that tidal disruption events (TDEs) caused by supermassive black holes (SMBHs) in nearby galaxies can account for the ultra-high-energy cosmic-ray (UHECR) hotspot reported recently by the Telescope Array (TA) and the warm spot by Pierre Auger Observatory (PAO). We describe the expected cosmic-ray signal from a TDE and derive the constraints set by the timescale for dispersion due to intergalactic magnetic fields and the accretion time of the SMBH. We find that TDEs in M82 can explain the hotspot detected by the TA regardless of whether the UHECRs are composed of protons or heavier nuclei. We then check for consistency of the hot and warm spots from M82 and Cen A with the full-sky isotropic signal from all SMBHs within the GZK radius. This analysis applies to any scenario in which the hot/warm spots are real and due to M82 and Cen A, regardless of whether TDEs are the source of UHECRs. We find that the isotropic flux implied by the luminosity density inferred from M82 and Cen A is bigger than that observed by roughly an order of magnitude, but we provide several possible explanations, including the possibility of a local overdensity and the possibility of intermediate-mass nuclei in UHECRs, to resolve the tension.

1 INTRODUCTION

In the past decade the ability to observe ultra-high-energy cosmic rays¹ (UHECRs) has increased significantly with the advent of the Pierre Auger Observatory (PAO) and the Telescope Array (TA). Recently, both the TA and the PAO have detected regions of excess UHECRs as compared to an isotropic background (Abbasi et al. 2014; Aab et al. 2015), with statistical significances of $\gtrsim 3\sigma$ and $\gtrsim 2\sigma$, respectively.

The sources of UHECRs are still unknown. One possibility is active-galactic-nucleus jets (Abraham et al. 2007). However, Farrar & Gruzinov (2009) derived a relation between the AGN electromagnetic luminosity and its UHECR luminosity. Zaw, Farrar & Greene (2009) then used the Veron-Cetty and Veron (VCV) catalogue, along with this luminosity relation, to infer that the observed AGN are not luminous enough to explain the full-sky UHECR flux. Gamma-ray bursts (GRBs) are also capable of producing UHECRs (Waxman 1995), but they would have to have a rather flat spectrum of UHECRs produced by an individual GRB and would have to yield over 100 times more energy to UHECRs than to photons in order to explain the full-sky flux (Farrar & Gruzinov 2009).

We consider a third mechanism as the dominant source of UHECRs, namely tidal disruption events (TDEs). A star is disrupted by a super massive black hole (SMBH) when it passes by close enough that tidal forces overcome the binding

energy of the star. Some fraction of the star then becomes bound to the SMBH and forms a short-lived accretion disk which produces an intense flare² (Rees 1988). Some of the TDEs produce jets which were first proposed as a source of UHECRs in Farrar & Gruzinov (2009), and then expanded upon in Farrar & Piran (2014), which showed that they can generate the luminosity required to account for the full-sky UHECR flux.

In 2014, the TA reported a “hot spot” of UHECRs (Abbasi et al. 2014) in a circle of radius 20° , centred at a right ascension of 146.7° and declination of 43.2° . He et al. (2016) tried to identify possible extragalactic sources for the hot spot, taking into account possible deflection of the UHECRs by Galactic and intergalactic magnetic fields. After accounting for random deflections by stochastic intergalactic magnetic fields (IGMFs), they drew a straight line through the images of the different rigidity bins of the events in the hotspot, expecting the source to lie along this line. Two possible sources were identified, M82 and Mrk 180. While Mrk 180 is located roughly 185 Mpc away, near the GZK radius, and is thus unlikely to be the source, M82 is a starburst galaxy only 3.8 Mpc away (Karachentsev & Kashibadze 2005) and moreover has a $\sim 3 \times 10^7 M_\odot$ SMBH at its cen-

¹ For the purpose of this paper, UHECRs will be defined as cosmic rays with energies above 57 EeV.

² The SMBH does not need to be an AGN—i. e. actively accreting from the accretion disk—in order for the disruption to cause rapid accretion. The in-falling gas from the disrupted star could form an accretion disk with rapid accretion resulting in a relativistic jet outflow (Farrar & Gruzinov 2009).

tre (Gaffney, Lester & Telesco 1993). The SMBH does not exhibit any AGN activity.

Likewise, the Pierre Auger Observatory has noted a “warm spot,” an excess of events in the direction of Centaurus A (Cen A). Cen A is also (coincidentally) approximately 3.8 Mpc away (Harris 2010), with a SMBH with a mass estimated to be $5 \times 10^7 M_\odot$. Unlike M82’s this SMBH does exhibit AGN activity and has a contentious jet.

In this paper we investigate whether the TA hotspot can be explained by TDEs in M82. We first derive basic constraints to the model parameters from timescale and energetic arguments. We surmise that the UHECR hot spot is in roughly steady state in which the UHECR flux results from several TDEs that have occurred within the timescale for dispersion of a burst signal due to deflections in the Galactic and intergalactic magnetic fields (although we do briefly consider the possibility that the hot spot arises from a single burst.) The model parameters are then a TDE rate in M82 and an efficiency for conversion of the stellar rest-mass energy into UHECRs. We find that there are indeed TDE rates, with plausible efficiencies, that are large enough to account for the hot spot yet small enough so that the time-averaged accretion rate onto the SMBH is still sub-Eddington. This conclusion follows if UHECRs are composed of protons and if there are also heavier nuclei in UHECRs, although the consistent parameter space is a bit smaller for heavier nuclei. Similar arguments apply to the warm spot from Cen A. We then investigate whether the UHECR luminosity density implied by the observed fluxes from the SMBHs in M82 and Cen A is consistent with the isotropic UHECR that is observed. We find that the isotropic flux inferred in this way is higher, by about a factor of 16, than the observed isotropic flux, but we point out several factors that might alleviate the apparent discrepancy.

The rest of this paper is organized as follows. In Section 2, we review briefly the evidence of the TA hot spot and the PAO warm spot and provide the fiducial values we use for the hot-spot and warm-spot fluxes as well as the isotropic UHECR intensity. In Section 3 we discuss the constraints to TDE scenarios for the UHECRs hot/warm spots that arise from energetics and timescale considerations. In Section 4 we consider constraints to the scenario that arise from consistency of the hot/warm-spot fluxes with the isotropic UHECR intensity. In Section 5 we summarize, review the successes and weaknesses of the TDE explanation for the hot/warm spots, consider some possible future measurements, and close with some speculations.

2 THE HOT AND WARM SPOTS

The TA Collaboration reports evidence (Abbasi et al. 2014) for a UHECR excess in a circle of 20° radius. Fang et al. (2014) estimate the specific (number) intensity J_H in this hot spot to be,

$$E^2 J_H = (4.4 \pm 1.0) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (2.1)$$

at an energy $E = 10^{19.5}$ eV. The hot-spot energy flux in UHECRs with energies > 57 EeV is $F_{\text{hs}} = \Omega_{20^\circ} \int_{57 \text{ EeV}}^\infty E J(E) dE$, where $\Omega_{20^\circ} \simeq 0.38$ sr is the hot-spot solid angle. The energy dependence of $J(E)$ at en-

ergies above 57 EeV is, however, is quite uncertain in the hot spot, and even for the full-sky flux [see, e.g., Fig. 7 in Kistler, Stanev & Yüksel (2014), which shows considerable disagreement between PAO and TA at the highest energies]. We therefore take the energy flux in the hot spot to be,

$$F_{\text{hs}} = 1.7 \times 10^{-8} F_{1.7} \text{ GeV cm}^2 \text{ s}^{-1}, \quad (2.2)$$

and keep the quantity $F_{1.7}$, which parametrizes our uncertainty in the flux, in our expressions below.

Likewise, we take the observed isotropic (energy) intensity above 57 EeV to be $I_o = 7.9 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (Kistler, Stanev & Yüksel 2014). Again, to be consistent with our treatment of the hot-spot flux, we take this to be the value of $E^2 J(E)$ at $E = 10^{19.5}$ eV. This isotropic flux appears below only in comparison to the hot-spot flux, and so it is appropriate to treat the full-sky flux in same way as the hot-spot flux.

We estimate the UHECR energy flux from Cen A implied by the PAO warm spot as follows: Abreu et al. (2010) finds 13 events within a circle of radius 18° , where 3.2 are expected from an isotropic distribution. We thus take the energy flux from Cen A to be $(13 - 3.2)/3.2 \approx 3$ times the isotropic energy flux in that circle, or

$$F_{\text{ws}} = 7.6 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1}, \quad (2.3)$$

keeping in mind the considerable uncertainty in this value.

3 TIME SCALES AND ENERGETICS

Our aim here is to understand whether TDEs from accretion of stars onto the SMBH in M82 may be responsible for the UHECR hot spot. We begin with some basic considerations, starting with time scales.

The hot spot is observed to be spread over an angular region of size $\theta \sim 20^\circ$. Such a spread is to be expected due to scattering in turbulent intergalactic magnetic fields (IGMFs) as the UHECRs propagate the 3.8 Mpc distance from M82, and there may be additional scattering (particularly for iron nuclei) from magnetic fields in the Milky Way. The rms deflection angle for a UHECR of charge Z is (He et al. 2016),

$$\delta_{\text{rms}} \approx 3.6^\circ Z E_{20}^{-1} r_{100}^{1/2} \lambda_{\text{Mpc}}^{1/2} B_{\text{nG,rms}}, \quad (3.1)$$

where $B_{\text{nG,rms}}$ is the rms strength of the magnetic field in nG, E_{20} is the UHECR energy in units of 10^{20} eV, $r_{100} = r/100$ Mpc is the distance over which the magnetic fields act, and λ_{Mpc} is the magnetic-field coherence length in units of Mpc. Consider first scattering in Galactic magnetic fields. Characteristic values might then be $\lambda_{\text{Mpc}} \sim 10^{-3}$, $r_{100} \sim 10^{-4}$, and $B_{\text{nG}} \sim 10^3$, implying Galactic deflection angles $\delta_{\text{rms}} \sim 1^\circ Z$, in rough agreement with Giacinti et al. (2010) and Farrar et al. (2013). We thus infer that for iron nuclei all the scattering could conceivably arise from Galactic magnetic fields, although it is more likely that if the UHECRs are protons, scattering in IGMFs is more important.

Either way, scattering in magnetic fields also gives rise

to a spread (Waxman 1995; Farrar & Piran 2014)

$$\begin{aligned}\tau &\simeq 3 \times 10^5 \left(\frac{r_{100} B_{\text{nG}}}{E_{20}} \right)^2 \lambda_{\text{Mpc}} Z^2 \text{ yr} \\ &\simeq 3.5 \times 10^5 \left(\frac{\delta_{\text{rms}}}{3.6^\circ} \right)^2 r_{100} \text{ yr.}\end{aligned}\quad (3.2)$$

Thus, if all the scattering takes place in the Milky Way, for which $r_{100} \sim 10^{-4}$, then $\delta_{\text{rms}} \sim 20^\circ$ implies a dispersion of $\tau \sim 1000$ yr in the UHECR arrival times. If scattering occurs primarily in IGMFs, then the spread in arrival times is more like $\tau \sim 4 \times 10^5$. *We thus infer that UHECRs are spread in arrival time by some magnetic-dispersion timescale $1000 \text{ yr} \lesssim \tau \lesssim 4 \times 10^5 \text{ yr}$, with protons more likely to fall near the higher end and iron nuclei closer to the lower end.*

We now consider energetics. If the observed flux in $E > 57$ EeV UHECRs in the hot spot is $F_{\text{hs}} \simeq 1.7 \times 10^{-8} F_{1.7} \text{ GeV cm}^{-2} \text{ sec}^{-1}$, then the implied isotropic-equivalent source luminosity is $L = 4\pi D^2 F \simeq 8.3 \times 10^{-7} F_{1.7} M_\odot c^2 \text{ yr}^{-1}$ (where $D = 3.8$ Mpc is the distance). If the observed UHECRs are due to a single TDE spread out over a time τ , then the isotropic-equivalent energy implied with $\tau \simeq 1000$ yr (more likely for iron nuclei) is $8.3 \times 10^{-4} F_{1.7} M_\odot c^2$. If the dispersion time is $\tau \simeq 4 \times 10^5$ yr, the more likely value for protons, then the isotropic-equivalent energy is $0.33 F_{1.7} M_\odot c^2$. Of course, if the TDE is beamed into a solid angle that subtends a fraction $\Omega_{\text{jet}} \sim 0.1$ of 4π , then the energy requirements can be relaxed by a factor ~ 10 . Still, we conclude that if UHECRs are iron nuclei, the hot spot is conceivably due to a single burst. If the UHECRs are protons, the energetics are prohibitive, unless the Milky Way magnetic-field parameters are altered so that the angular spread in the hot spot arises from scattering in the Milky Way. Even if the energetics can somehow be worked out, the notion that we are seeing a hot spot just from M82 because of some chance occurrence (an extraordinarily energetic TDE at just the right time) is unsatisfying, and even more unsatisfying if we must also explain the warm spot as some similar chance occurrence in Cen A.

Another possibility is that the observed hot spot arises not from a single TDE, but from a number of TDEs in M82. This may occur if the dispersion τ in arrival times exceeds the typical time Δt between TDEs in M82. If so, then we are seeing UHECRs from $N \simeq (\tau/\Delta t) \gtrsim 1$ bursts at any given time. The hot-spot flux in this case will vary by a fractional amount $\sim N^{-1/2}$ over timescales $\sim \tau$. However, over the ~ 5 -yr observation, the observed flux will remain effectively constant. This scenario, as we will now show, is plausible.

We suppose that stars (which we assume for simplicity to all have a mass M_\odot) are swallowed by the SMBH with a rate Γ . We then suppose that only a fraction ζ produce the type of jets that can accelerate UHECRs and that a fraction ξ of the stellar rest-mass energy $M_\odot c^2$ goes into UHECRs. We further suppose that the UHECR emission may be beamed into a fraction Ω_{jet} of the 4π solid angle of the sphere. In order to obtain the observed UHECR hot-spot flux in steady state, we require that stars be swallowed by the SMBH at a rate,

$$\Gamma = 8.3 \times 10^{-7} \left(\frac{\Omega_{\text{jet}} F_{1.7}}{\xi \zeta} \right) \text{ yr}^{-1}. \quad (3.3)$$

The mean time between UHECR-producing events is

$$\Delta t = (\zeta \Gamma)^{-1} = 1.26 \times 10^6 \frac{\xi}{\Omega_{\text{jet}} F_{1.7}} \text{ yr.} \quad (3.4)$$

If this mean time is to be smaller than the magnetic-dispersion time τ , we require

$$\frac{\xi}{\Omega_{\text{jet}} F_{1.7}} \lesssim 0.31 \tau_4, \quad (3.5)$$

where τ_4 is the magnetic-dispersion time in units of 4×10^5 yr.

We now compare the mass-accretion rate implied by equation (3.3) with the Eddington rate $\dot{M} = L_{\text{Edd}}/c^2 \simeq 3.8 \times 10^{45} M_3 \text{ erg s}^{-1}/c^2$, where M_3 is the SMBH mass in units of $3 \times 10^7 M_\odot$, for M82. Assuming that half of the disrupted star's mass is accreted, we find that the mass-accretion rate is smaller than Eddington if

$$\frac{\xi}{\Omega_{\text{jet}} F_{1.7}} \gtrsim 6.0 \times 10^{-6} M_3^{-1} \zeta^{-1}. \quad (3.6)$$

It is not, strictly speaking, required that this condition be respected. It is conceivable that a SMBH could appear quiescent, even with a super-Eddington time-averaged mass-accretion rate, if the accretion is episodic. Still, the scenario may be a bit more palatable if we do not have to wave away a super-Eddington accretion rate in this way. Or put another way, it is simply interesting to note that the scenario can work with a sub-Eddington time-averaged accretion rate as long as equations (3.5) and (3.6) are satisfied, or as long as

$$\zeta \gtrsim \frac{1.9 \times 10^{-5}}{\tau_4 M_3}. \quad (3.7)$$

This quantity must be $\zeta \leq 1$, and is estimated to be $\zeta \sim 0.1$ (Farrar & Piran 2014) (although that is a value for the average over all SMBHs, and does not necessarily apply to a single SMBH). Such a value is easily accommodated if $\tau_4 \sim 1$, as we might expect for UHECR protons, and even fits for heavier nuclei, for which $\tau_4 \sim 2.5 \times 10^{-3}$.

We have thus shown that the TA hot spot can be explained as a roughly steady-state phenomenon by the sub-Eddington capture and tidal disruption of stars by the SMBH in M82. The scenario works independent of whether the UHECRs are protons or iron nuclei, although the timescale parameter space is a bit narrower for iron nuclei, a consequence of the larger deflection of iron nuclei in the Milky Way magnetic field.

4 ISOTROPIC FLUX

We now investigate whether the isotropic UHECR flux implied by this scenario is consistent with that observed under the assumption that the UHECR luminosity of M82 (and of Cen A) are fairly typical for such SMBHs. This analysis applies not only to the hypothesis that TDEs are responsible for the hot and warm spots, but to any scenario in which there are hot/warm spots associated with Cen A and M82.

We begin with a simple analysis. The isotropic-equivalent luminosities of M82 and Cen A are, respectively, $2.9 \times 10^{43} \text{ GeV s}^{-1}$ and $1.4 \times 10^{43} \text{ GeV s}^{-1}$. Both SMBHs are at a distance $R \lesssim 4$ Mpc, and so the UHECR luminosity density in a 4-Mpc sphere around us is $\rho_L \simeq 5.4 \times 10^{-33} \text{ GeV cm}^{-2} \text{ s}^{-1}$. If the UHECR emissions from Cen

A and M82 are both beamed into a fraction Ω_{jet} of the 4π solid angle, then ρ_L is reduced by Ω_{jet} . If M82 and Cen A are not atypical, though, then there must be $\sim \Omega_{\text{jet}}^{-1}$ other beamed UHECR sources, aimed in other directions, for every source that we see. This then cancels the Ω_{jet} beaming reduction leaving ρ_L unchanged. Since both Cen A and M82 appear, in the jetted-TDE scenario, to be aimed at us, we infer that Ω_{jet} is unlikely to be small in this scenario. The tension we will find below between the hot/warm-spot fluxes and the isotropic intensity can be relaxed, though, if both Cen A and M82 just happen to be highly beamed and both in our direction. If our local neighborhood is not atypical, then ρ_L provides an estimate of the universal UHECR luminosity density. If the local density is greater by a factor f_ρ than the cosmic mean density, then the universal UHECR luminosity density is ρ_L/f_ρ .

The isotropic UHECR intensity (energy per unit area per unit time per unit solid angle) is

$$I = \int_0^R dr r^2 f(r) \frac{\rho_L}{4\pi r^2} = \frac{\rho_L}{4\pi} \int_0^R dr f(r) = \frac{\rho_L R}{8\pi}, \quad (4.1)$$

where R is the GZK radius, and the second equality is obtained by approximating the fraction of UHECR energy emitted at a distance r that makes it to us to be $f(r) \simeq 1 - (r/R)$ (Kotera & Olinto 2011). If the TA hot spot and PAO warm spot are real and attributed to M82 and Cen A, respectively, then the isotropic UHECR flux should be $I = 1.37 \times 10^{-7} F_{1.7} f_\rho^{-1} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. This is, for $f_\rho = 1$, 16 times greater than the isotropic intensity $I_o = 7.9 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The discrepancy cannot be alleviated with a smaller value of $F_{1.7}$ because, as discussed after equation (2.2), we are using the specific intensities at $E \simeq 10^{19.5} \text{ EeV}$, which are fairly well determined, as proxies for the full energy flux and isotropic intensity.

It is, however, likely that the tension can be alleviated, at least in part, with a value $f_\rho > 1$. The local density is uncertain, but as one indication of the value of f_ρ , we can use the total SMBH in the $R \simeq \text{Mpc}$ sphere, assuming that the UHECR luminosity density is proportional to the density of mass SMBHs. In addition to the SMBHs in Cen A and M82, there is also the $\sim 4 \times 10^6 M_\odot$ SMBH in the Milky Way and the $\sim 10^8 M_\odot$ SMBH in Andromeda, as well as a $\sim 10^6 M_\odot$ SMBH in M32. This totals to $\sim 2 \times 10^8 M_\odot$ in SMBHs within a distance $R \simeq 4 \text{ Mpc}$ implying a local SMBH density $\simeq 7.5 \times 10^5 M_\odot \text{ Mpc}^{-3}$, roughly 3 times the universal SMBH density $\simeq 2.9 \times 10^5 M_\odot \text{ Mpc}^{-3}$ (Dzanovic et al. 2007). There is still residual factor of ~ 5 discrepancy that remains, even accounting for this $f_\rho \sim 3$, that must be accounted for if the TDE explanation for the TA and PAO hot spots is to remain viable. This level of discrepancy is, we believe, given the order-of-magnitude nature of the analysis, as well as the measurement and astrophysical uncertainties, not necessarily fatal for the TDE scenario. The local luminosity density ρ_L we inferred could have been reduced a bit by considering a sphere of slightly larger radius; there are uncertainties almost of order unity in the measured fluxes; and the Poisson fluctuation in our inference of ρ_L is also of order unity.

So far we have been using the UHECR flux from M82 and Cen A to infer a luminosity density, and the uncertainty from small-number statistics has been noted above. There is, however, an additional uncertainty that

may arise from the dependence of the mean TDE rate on SMBH mass. SMBHs are distributed with a mass function dn/dM (Dzanovic et al. 2007; Caramete & Biermann 2010), and there is evidence that the TDE rate varies with the SMBH mass. We infer an UHECR luminosity density from measurement of the UHECR flux from one or two $\sim 3 \times 10^7$ SMBHs. Suppose, though, that the TDE rate varies as $\Gamma(M) = \Gamma(M = 3 \times 10^7 M_\odot)(M/3 \times 10^7 M_\odot)^{-\beta}$. The luminosity density we infer from the measured M82 flux would then be $L_{\text{tde}} \int (dn/dM)(M/3 \times 10^7 M_\odot)^{-\beta}$, where L_{tde} is the UHECR luminosity from one burst. If we then use the best estimate $\beta \simeq 0.22$ from Stone & Metzger (2016), the SMBH mass function from Dzanovic et al. (2007), and integrate from $10^5 M_\odot$ (below which there is little evidence for SMBHs) to $10^8 M_\odot$ (above which stars will be swallowed without being tidally disrupted (Magorrian & Tremaine 1999)), we find—unfortunately for the TDE scenario—a luminosity density ~ 1.7 times higher. This power-law index β is, however, quite uncertain, and if we suppose that it is instead $\beta \simeq 0.5$, then the inferred luminosity density is decreased by ~ 0.5 . This may thus provide some wiggle room for the tension between the M82 and Cen A fluxes and the isotropic intensity, although is unlikely to be the entire explanation. Changes to the upper and lower limits of integration do not alter this conclusion. We do note that the masses of the SMBHs in Cen A and M82 are quite similar, both around $(3-5) \times 10^7 M_\odot$. If, for some reason, the TDE rate were to be maximized for SMBHs of this mass, and smaller for SMBHs of both lower and higher masses, then the universal UHECR luminosity could be reduced significantly relative to what we inferred above. In this case, the high fluxes toward M82 and Cen, relative to the isotropic intensity, would be a consequence of our chance proximity to two SMBHs of this specific mass.

The tension between the hot/warm-spot fluxes and the isotropic intensity may also be relaxed if UHECR consist at the source, at least in part, of other nuclei, like helium, carbon, nitrogen, or oxygen. The path length of such nuclei through the intergalactic medium is far smaller than the $\sim 200 \text{ Mpc}$ GZK distance of protons and iron nuclei (Kotera & Olinto 2011). If there is significant UHECR production in such nuclei, then the isotropic intensity inferred from the measured $D \lesssim 4 \text{ Mpc}$ luminosity density will be smaller. Such a scenario implies a different observed UHECR composition in the hot/warm spots and in the isotropic component. There may already be some evidence for intermediate-mass nuclei in UHECRs Aab et al. (2014).

5 DISCUSSION: TDE SCORECARD

Here we have investigated the possibility that tidal disruption events fueled by the accretion of stars onto the SMBH in M82 could account for the hot spot reported by the Telescope Array and that TDEs onto the SMBH in Cen A could explain the warm spot seen by the Pierre Auger Observatory toward Cen A. Given the measurement uncertainties and considerable astrophysical uncertainties, it is difficult to make precise statements about the viability of the scenario. Although there are some tensions at the order-of-magnitude level, there is, as far as we can tell, no silver bullet that

rules the scenario out at the level of more than an order of magnitude.

Our conclusions are as follows: Energetics make it unlikely, although not impossible, that the hot spot toward M82 is the result of a single burst, a tension that is probably greater if UHECRs are protons rather than iron nuclei. Dispersion in galactic and intergalactic magnetic fields disperse the UHECR arrival times. This magnetic-dispersion time is, if anything, likely higher for protons than for iron nuclei. The single-burst scenario is also unappealing as it implies that the hot spot is evanescent, something that we see as a chance occurrence. This chance event is made even less likely if the warm spot toward Cen A is also explained another chance event.

The energetics requirements are relaxed, though, if the UHECRs in the hot spot result from a number of TDEs in M82 that have occurred over a magnetic dispersion time, a scenario in which the UHECR fluxes in the hot/warm spots are roughly in steady state. The required efficiency of UHECR production in each TDE event can then be reduced at the expense of an increased TDE rate. We do show, though, that the TDE rates can still remain low enough so that the time-averaged accretion rate in M82 remains sub-Eddington, something that may be desirable, though not necessarily required, to explain the quiescent nature of the SMBH in M82. (This is less of a concern, of course, for Cen A, which is quite active.) This latter, softer, requirement, is satisfied, though, only at the expense of introducing a slight tension in the required UHECR efficiency per TDE. That tension can be reduced if the TDE is highly beamed. Significant beaming introduces, however, the notion that the UHECR flux from M82 results from our chance position within the TDE's jet, an ingredient that is less appealing if we must also explain the PAO warm spot in terms of TDEs from Cen A's SMBH. Any significant beaming requirement for Cen A would also be more difficult given that the radio observed jet in Cen A is not pointed toward us.

We note that the time between jetted TDEs in our scenario is a bit higher than the rate expected from existing TDE statistics. Scalings between TDE rates and SMBH masses derived in Stone & Metzger (2016) suggest that the characteristic time between TDEs in a $3 \times 10^7 M_\odot$ SMBH is $\Gamma^{-1} \sim 10^4$ yr. Farrar & Piran (2014) estimate further that only a fraction $\zeta \sim 0.1$ of TDEs are jetted. If we take this value for M82, then the time between UHECR-producing events is greater than the magnetic-dispersion time. There are, however, considerable uncertainties in these estimates, and there may also be considerable variation between the jetted fraction for one particular SMBH and the mean inferred by averaging over all SMBHs.

We then investigated the isotropic flux of UHECRs that is expected if the sources of UHECRs in M82 and Cen A are not atypical. This analysis applies not only to the hypothesis that the UHECR sources in M82 and Cen A are TDEs, but to any scenario in which there are hot/warm spots from Cen A and M82. The observed UHECR fluxes from M82 and Cen A imply a local UHECR luminosity density. We find that if the universal UHECR luminosity density is taken to be this local luminosity density, then the isotropic UHECR intensity is about 16 times larger than that observed. There is, however, some evidence that the local mass density in SMBHs is higher, perhaps by ~ 3 , than the universal den-

sity. Even so, there is still a tension, at the ~ 5 level, between the hot/warm spot fluxes and the isotropic intensity. Possible explanations for this residual tension may arise from our underestimate of the local overdensity; small-number statistics in the number of SMBHs; uncertainties in the characterization of the hot/warm spots; a mixed composition of UHECRs including intermediate-mass nuclei with smaller GZK cutoffs; and/or some SMBH-mass dependence of the TDE rate.

It is interesting to wonder whether the SMBH $\sim 4 \times 10^6 M_\odot$ SMBH at the center of Milky Way (Ghez et al. 2008) should produce UHECRs. The answer is probably not. Assuming the Milky Way is a core galaxy, the expected time, from Stone & Metzger (2016), between TDEs for the Milky Way's SMBH is 3.9×10^4 yr. As discussed above, the magnetic-dispersion time within the Milky Way can be, for reasonable magnetic-field parameters, quite a bit smaller than this. It is thus not surprising that we do not see an UHECR hot spot toward the Galactic center, even if our SMBH does produce TDEs at the expected rate.

Future measurements should help shed additional light on the viability of TDEs as the sources of UHECRs. The viability of the TDE scenario for the isotropic flux has been discussed in Farrar & Gruzinov (2009); Farrar & Piran (2014), but if the hot/warm spots are real and attributed to M82 and Cen A, then there are additional challenges discussed above. It will be interesting to see if the evidence for the hot and warm spots continues with additional data, and if so, the characterization of those fluxes should improve. There may be differences, which we will explore elsewhere, in the energy distribution of UHECRs in the hot/warm spots, that come from 3.8 Mpc, versus those in the rest of the sky, which come from much greater distances and thus experience greater photo-pion absorption.

There may also be signatures in ultra-high-energy neutrinos expected to be produced alongside UHECRs. Although the arrival times of UHECRs are spread out by magnetic fields, neutrinos travel in a straight path. While some UHE neutrinos may be produced during photo-pion or photo-disintegration in transit from the source, neutrinos produced during the TDE should arrive in a single burst, roughly coincident with the TDE light arrival time. Detection of UHE neutrinos from a TDE (any TDE, not necessarily one in M82 or Cen A) would thus significantly bolster the case for TDEs as a source of UHECRs. However, given the low fluxes and TDE rates, nonobservation of neutrinos from TDEs is unlikely to constrain the scenario.

Before closing, we speculate on the possibility that the IMBH in M82 Patruno et al. (2006); Pasham, Strohmayr & Mushotzky (2014) (should the evidence for that IMBH survive) may have something to do with the TA hot spot. It may be possible for IMBHs to produce their own TDEs. A TDE would need to occur close to the innermost stable circular orbit of the IMBH in order to accelerate the in-falling matter and produce a flare. A main-sequence star would be disrupted before then, but a white dwarf could possibly survive until it gets close enough to an IMBH to produce a TDE with an intense flare. Another possibility is that IMBHs might perturb the orbits of stars in a way similar to the Kozai mechanism (Perets, Hopman & Alexander 2007), and thus increase the rate of TDEs in the host galaxy. The tension with the

isotropic UHECR intensity might thus be explained by an IMBH-enhanced TDE rate in M82 relative to what it would be otherwise.

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